

# Fading of the X-ray flux from the black hole in the NGC 4472 globular cluster RZ 2109

Thomas J. Maccarone

*School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ, United Kingdom*

Arunav Kundu

*Eureka Scientific, 2452 Delmer Street Suite 100, Oakland, CA 94602-3017, USA*

Stephen E. Zepf

*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

Katherine L. Rhode

*Department of Astronomy, Indiana University, 727 East 3rd Street, Bloomington, IN 47405-7105, USA*

## ABSTRACT

We present the results of new X-ray observations of XMMU 122939.7+075333, the black hole (BH) in the globular cluster RZ 2109 in the Virgo Cluster galaxy NGC 4472. A combination of non-detections and marginal detections in several recent *Swift* and *Chandra* observations show that the source has varied by at least a factor of 20 in the past 6 years, and that the variations seem not just to be “flickering.” This variation could be explained with changes in the absorption column intrinsic to the source no larger than those which were previously seen near the peak of the 1989 outburst of the Galactic BH X-ray binary V404 Cyg. The large amplitude variations are also a natural expectation from a hierarchical triple system with Kozai cycles – the mechanism recently proposed to produce BH-white dwarf (WD) binaries in globular clusters. On the other hand, variation by such a large factor on timescales of years, rather than centuries, is very difficult to reconcile with the scenario in which the X-ray emission from XMMU 122939.7+075333 is due to fallback of material from a tidally destroyed or detonated WD.

**Key words:** globular clusters:general – stellar dynamics – stars:binaries – X-rays:binaries

## 1 INTRODUCTION

The dense stellar systems in globular clusters can produce a variety of classes of exotic binary stars. Until recently, there was no convincing evidence for any BH X-ray binaries in globular clusters. All of the Milky Way’s globular clusters which contain bright X-ray binaries have shown Type I X-ray bursts, which are caused by thermonuclear runaway on a solid surface, requiring a neutron star (NS) accretor. Two of the clusters contain pairs of X-ray binaries which have become bright, although even in those cases, both objects are believed to be NSs. In NGC 6440, two distinct pulse periods have been seen from the cluster (Altamirano et al. 2010), while in M 15, the source which is not thought to be a burster is likely to be a NS based on Doppler tomography (van Zyl et al. 2004).

With the advent of the *Chandra* X-ray observatory, with

its excellent angular resolution and sensitivity, it became possible to associate X-ray sources with luminosities in excess of  $10^{39}$  ergs/sec with globular clusters (e.g. Sarazin et al. 2000; Angelini et al. 2001). However, such luminosities can potentially be produced by multiple bright NSs in the same cluster; strong variability is one of the few ways to distinguish between a single BH X-ray binary and many bright NSs (Kalogera et al. 2004). In recent years, several globular cluster X-ray sources have shown variability by amounts greater than the Eddington luminosity for a NS (Maccarone et al. 2007; Brassington et al. 2010; Shih et al. 2010; Maccarone et al. 2010), providing the first strong evidence for BHs in globular clusters. These discoveries have been particularly exciting in view of theoretical work suggesting that stars much heavier than the mean stellar component in a cluster (such as stellar mass BHs) should be efficiently

ejected (Spitzer 1969). On the other hand, more recent, more detailed numerical calculations have found black hole retention fractions similar to those for NSs (Mackey et al. 2007; Moody & Sigurdsson 2009).

XMMU 122939.7+075333 in the globular cluster RZ 2109 (Rhode & Zepf 2001) in NGC 4472 was the first ultraluminous globular cluster X-ray source to show strong X-ray variability (Maccarone et al. 2007). Additionally, this source shows strong, broad [O III] emission lines [Zepf et al. 2007; 2008 (Z08)]. The emission lines are sufficiently strong and broad that they cannot be produced through virial motions around a BH less than about  $3 \times 10^4 M_\odot$  (Z08; Porter 2010), so the system is much more likely to be an accreting stellar mass BH with a strong disk wind than an intermediate mass BH (Z08), since such winds are likely only near the Eddington luminosity (e.g. Proga 2007).

One way to account for the large ratio of oxygen relative to other species in the optical spectrum is through a WD or some other highly evolved donor star (Gnedin et al. 2009). The high luminosity then implies that the donor star is likely to be a WD in a short orbital period binary. Recently, Ivanova et al. (2010) have suggested that the most efficient way to produce such a system is to make it the inner binary system in a hierarchical triple star system, with the eccentricity induced by the Kozai (1962) cycles grinding down the orbit into contact on a short timescale. In this Letter, we report on the discovery of large amplitude variability of this source, consistent with it turning off as an X-ray source, and discuss it in terms of eccentricity-induced accretion rate cycles. We also consider the possibility that the source varies because of changes in the foreground absorption.

## 2 DATA

### 2.1 Observations already in the literature

Several previous observations have been made with sufficiently good angular resolution to allow for measurements of the flux of XMMU 122939.7+075333. The dates and luminosities of the published and new observations of XMMU 122939.7+075333 are presented in Table 1. Most of the past observations have been previously summarized by Shih et al. (2008), but we repeat the results here for completeness. ROSAT observed NGC 4472 with its High Resolution Imager for 27000 seconds of live time spread over June and July of 1994. XMMU 122939.7+075333 was reported as IXO 60 in the “intermediate X-ray object” catalog of Colbert & Ptak (2002). They estimated a source luminosity of  $10^{39.9}$  ergs/sec from 2-10 keV, assuming a  $\Gamma = 1.7$  power law. Due to the poor spectral resolution of the HRI combined with the fact that the measurements were actually made from 0.1-2.4 keV, there is considerable uncertainty in the counts-to-energy conversion factor. Re-evaluating the flux for XMMU 122939.7+075333 using a softer spectral model can reduce the inferred luminosity dramatically; we have taken the observed count rate of  $4 \times 10^{-3}$  counts/sec and computed fluxes using the W3PIMMS tool and have found that for a 0.2 keV blackbody, the inferred luminosity is  $3 \times 10^{39}$  ergs/sec. We find it safe to say only that the luminosity during this epoch is likely to be greater than  $10^{39}$  and less than  $10^{40}$  ergs/sec.

Observatory	Date	Luminosity
<i>Einstein</i>	July 1979	$\lesssim 10^{40}$ ergs/sec
<i>ROSAT</i>	June-July 1994	$\sim 5 \times 10^{39}$ ergs/sec
<i>Chandra</i>	12 June 2000	$5 \times 10^{39}$ ergs/sec
<i>XMM-Newton</i>	5 June 2002	$4 \times 10^{39}$ ergs/sec
<i>XMM-Newton</i>	1 January 2004	$4 \times 10^{39}$ ergs/sec
<i>Swift</i>	2007 Dec./2008 Jan.	$< 3 \times 10^{39}$ ergs/sec
<i>Chandra</i>	27 February 2010	$\approx 1 \times 10^{38}$ ergs/sec
<i>Swift</i>	late March 2010	$< 1.5 \times 10^{39}$ ergs/sec

**Table 1.** The X-ray luminosities of XMMU J122939.7+075333 from long-look observations. The ROSAT observation has a factor of  $\sim 2$  uncertainty in the luminosity due to uncertain count-to-energy conversion. The 2004 XMM observation entry is the source luminosity in the bright epoch. It is also the source luminosity in the faint epoch under the assumption that its variability within the observation is due to a change in absorption intrinsic to the source. The source luminosity in the faint epoch if one accounts only for the Galactic foreground absorption is about a factor of 3 lower. The 2010 *Chandra* detection is statistically marginal. The *Swift* upper limits are given at the 95% confidence level.

XMMU 122939.7+075333 was observed by *Chandra* on 12 June 2000, showing a soft spectrum (well-fitted by a  $kT_{in} = 0.2$  keV disk blackbody model) with a luminosity of about  $5 \times 10^{39}$  ergs/sec (Shih et al. 2008); by XMM-Newton on 5 June 2002 with a luminosity of  $4 \times 10^{39}$  found from the 2XMM survey (Watson et al. 2009). Finally, it was observed by XMM on 1 January 2004, where the rapid variability was found. In the 2004 XMM observation, the source was at  $4 \times 10^{39}$  for about 10 kiloseconds, then dropped by a factor of 7 in count rate, with the drop consistent with a change in the foreground absorption column, with no change in the intrinsic source spectrum (Maccarone et al. 2007). The spectrum of the faint part of the XMM observation would have produced  $\sim 200$  counts in the 2010 *Chandra* observations – the variability is clearly strong and significant.

We note additionally that *Einstein* observed NGC 4472 in 1978, and did not make a detection. The noise level in the data set for the off-axis detected sources was  $2 \times 10^{-3}$  cts/sec (Harris et al 1993), so the non-detection implies a count rate below about  $1 \times 10^{-2}$  cts/sec. Using W3PIMMS to convert this count rate to a luminosity, we find an upper limit of  $1.5 \times 10^{40}$  ergs/sec assuming a  $\Gamma = 1.7$  power law, and about half that using blackbody models in the range from  $kT_{BB} = 0.2 - 0.5$  keV in temperature, assuming a distance of 16 Mpc (Macri et al. 1999).

### 2.2 New Chandra observations

We observed NGC 4472 with *Chandra* on 27 February 2010. The primary motivation for that observation was to look for variability from bright sources in the inner regions of the galaxy, so XMMU 122939.7+075333 lies on the edge of the ACIS-S3 chip. We produced an exposure map to determine the effective exposure time at the source position and found it to be about 20000 seconds.

We have run WAVDETECT on the filtered events list, using the standard  $10^{-6}$  null hypothesis probability which is set to ensure that there will typically be  $\sim 1$  chance detection over an ACIS chip. No source is detected at the position of RZ 2109. Given the vignetting and dither pattern’s effects,

the effective exposure time at the source’s position, as estimated from the exposure map, is about 20000 seconds. We then use aperture photometry with radius 12.2 pixels, appropriate for containing all the flux from the source at this angle off-axis<sup>1</sup>, and we detect 19 counts between 0.5 and 8 keV. The expected rate of background photons over a region this size at this position is 10.8. The net number of counts in the region is then  $8.2 \pm 3.3$  – giving a roughly 1% chance of a fluctuation in the background producing this flux at this position. Using W3PIMMS with either a  $\Gamma = 1.7$  power law or a  $kT = 1$  keV blackbody (spectra roughly consistent with the low/hard and high/soft states for stellar mass black holes), we find a flux of about  $4 \times 10^{-15}$  ergs/sec/cm<sup>2</sup>, which corresponds to a source luminosity of  $10^{38}$  ergs/sec. The  $3\sigma$  upper limit from the source is about  $2 \times 10^{38}$  ergs/sec.

### 2.3 Swift observations

We have triggered the Swift X-ray Telescope to observe XMMU 122939.7+075333 five times – on 2007 December 25 and 2 January 2008, roughly simultaneously with our Keck spectroscopy (Zepf et al. 2007;2008), and three times in late March of 2010 in response to the non-detection in the *Chandra* observations presented above. The observation ID numbers are 0031078001 through 0031078005. We also note that an additional short XMM observation was made at about the same time as the Keck spectrum, but that strong flaring background prevented those data from being useful.

We analyse the Swift data using the standard cleaned events files, after final versions had been entered into the archive. A quick visual inspection of the data revealed that the source would be, at best, marginally detected by Swift in our observations. For that reason, we use a 20” aperture to extract a number of detected photons. This radius corresponds to the 75% encircled energy region for Swift XRT (need ref for Swift XRT PSF), but it allows for a much lower background count rate than using the standard 90% encircled energy region of 47”. We extract events in channels 50-500 (approximately 0.5-5 keV). We use a 200” aperture off-axis region to estimate the background count rate.

We combine the two observations in 2007/2008 with one another to make “Swift epoch 1” and the three observations from 2010 to make “Swift epoch 2”. For Swift epoch 1, we detect 4 source counts, and 95 background counts in a total of 3843 seconds. Given that the background region has a radius ten times as large as the source region, we estimate that the source region should contain  $0.95 \pm 0.09$  background counts. There is thus a 1.6% chance that the 4 detected counts could be produced by Poisson fluctuations of the background. If we assume a spectrum of an 0.2 keV blackbody for the source convolved with the foreground Galactic absorption and use W3PIMMS to convert counts to energy, then the inferred source X-ray luminosity is about  $10^{39}$  ergs/sec for this marginal detection. A Poisson process with mean of 9.3 counts will produce 4 or fewer detected counts 5% of the time. We can then take as an upper limit for the source count rate 8.3 counts over the time interval, giving an upper limit to the source luminosity of about

$3 \times 10^{39}$  ergs/sec, with some additional uncertainty based on the spectral model used to convert counts to energy. This observation thus provides weakly suggestive evidence that XMMU 122939.7+075333 had already started to fade in the X-rays by late 2007. The data from Swift epoch 2 show 1 source photon and 134 background photons in 5003 seconds of summed exposure time – the background count rate per pixel is nominally higher than the source region rate. The 95% confidence level upper limit on the number of source plus background counts is about 5.8 – yielding an upper limit to the net source count rate of about 4.5 counts in 5000 seconds – about half the upper limit in 2007 with Swift. In this case, it is clear that the source must have either faded or changed spectrum significantly since the deep *Chandra* and XMM observations taken from 2002 through 2004.

## 3 DISCUSSION

Three possibilities have been laid out for the nature of XMMU 122939.7+075333. One of these possibilities is that the source is a red giant-black hole binary, with the change in brightness in the 2004 XMM observation caused by a grazing eclipse of the inner accretion disk by a puffy, precessing outer disk (Shih et al. 2008); this possibility is no longer viable because the large ratio of [O III] to Balmer emission strongly favors an evolved donor star. Alternatively, the accreting object may be a stellar mass black hole accreting from a WD in a short period binary system, or it may be the result of a tidal detonation of a WD by an intermediate mass BH (Irwin et al. 2010). We can then consider the implications of the X-ray variability on these different classes of models.

### 3.1 WD-BH binary and triple models

The strong variability seen from XMMU 122939.7+075333 is easy to explain in a model where the accretion is taking place in a hierarchical triple star system, with the inner binary being WD-BH X-ray binary. Such a scenario is the preferred means for forming a WD-BH X-ray binary according to the theoretical work of Ivanova et al. (2010).

An aspect of the triple star system that was not explored by Ivanova et al. (2010) may have profound consequences for the observability of the system. The Kozai cycles that are invoked for grinding down the system to Roche lobe overflow should continue after the system has come into Roche lobe overflow. The eccentricity of the inner binary will then continue to oscillate. It has been shown previously that even small eccentricities can produce large changes in mass accretion rates (Hut & Paczynski 1984) – the mass transfer rate should increase as the density of material at the Roche lobe radius. To first order, that should give a dependence as  $\exp(eR/h)$ , where  $e$  is the eccentricity of the binary,  $h$  is the scale height of the star, and  $R$  is the radius of the star. The value of  $h/R$  is typically  $10^{-4}$  for a main sequence star, and should be a bit smaller for WDs unless they are very hot. A triple system could then be expected to produce an accretion rate which is modulated substantially on the timescale for which the eccentricity changes due to the Kozai cycles, even for very small eccentricity changes.

A convenient form for the period of eccentricity varia-

<sup>1</sup> <http://cxc.harvard.edu/ccw/proceedings/03-proc/presentations/allert/index.html>

$$P_e = P_1 \left( \frac{m_0 + m_1}{m_2} \right) \left( \frac{a_2}{a_1} \right)^3 (1 - e_2^2)^{\frac{3}{2}}, \quad (1)$$

where  $P_1$  is the period of the inner binary,  $m_2$  is the mass of the outer star, and  $a_2$  is the orbital separation of the outer star from the center of mass of the inner binary is given by Ford et al. (2000) – see also Mazeh & Shaham (1979). In the case that  $m_2 \ll (m_0 + m_1)$ , we can use Kepler’s third law to solve for  $P_2$ , the period of the outer star in the hierarchical triple:

$$P_2 = \sqrt{P_e P_1 \left( \frac{m_2}{m_0 + m_1} \right) (1 - e^2)^{-\frac{3}{2}}}, \quad (2)$$

with a correction term of  $\sqrt{\frac{m_0 + m_1 + m_2}{m_0 + m_1}}$  in the case that  $m_2$  is large enough for this term to be important. The accretion rate for XMMU 122939.7+075333 seems to have been roughly constant from 1992 to 2004, but to have changed substantially between 2004 and 2010. Taking illustrative values  $m_0 \approx 10M_\odot$ ,  $m_1 = m_2 = 0.1M_\odot$ ,  $P_e = 40$  years, and  $P_1 = 10$  minutes, gives  $P_2$  of 60 days, a reasonable value for the period of the outer star in a hierarchical triple formed dynamically in a globular cluster, as the binary will still be “hard.”

We note that the stellar mass BH scenarios for XMMU 122939.7+075333 require a mildly super-Eddington accretion rate. The luminosity of XMMU 122939.7+075333 in its bright states is above the Eddington luminosity for a stellar mass BH, and the spectral shape of the source is considerably softer than those for stellar mass BHs. These properties of the source can all be reconciled with the idea that this source, in its bright states is in the “ultraluminous state” (Gladstone et al. 2009 – see also Soria et al. 2007 for a somewhat different scenario producing similar observables), in which a cool photosphere develops in the inner accretion flow due to radiation pressure. One would also expect strong disk winds from such radiation pressure dominated systems (e.g. Oosterbroek et al. 1997; Blundell et al. 2001). This gives good reason to believe that the  $\dot{m}$  may be changing substantially over the 10 year bright phase from 1994-2004, even if the luminosity changes rather little – the X-ray luminosity in the ultraluminous state is likely to change much more slowly than linearly with mass transfer rate. In the context of this scenario, the disk wind may also be responsible for obscuring the inner accretion disk, with variations in the disk wind causing events like the decrease in brightness seen in the 2004 XMM observation.

### 3.2 Tidal destruction scenarios

In scenarios where the broad [O III] emission lines arise from outflows generated in a tidal disruption or detonation of a white dwarf, *ad hoc* scenarios must be invoked for strong variability of the X-ray source. Models of the mass flow of tidal disruption debris onto the disruptor have been calculated for the case of supermassive BHs disrupting main sequence and giant stars. They find  $\dot{m} \propto t^{-5/3}$  from analytic calculations (Rees 1988) and from smoothed particle hydrodynamics calculations (Bogdanović et al. 2004), with slightly shallower relations when accretion is modulated by a disk (Cannizzo et al. 1990).

A generic feature of the solutions is that the luminosity decline is not terribly steep. Given that the luminosity of

XMMU 122939.7+075333 varied by factors of a few, at most, in the observations collected from the 1992 ROSAT observations through the 2004 XMM observations, a variation of a factor of 20 or so from 2004 to 2010 should not be expected. Since the time baseline is longer between the ROSAT observations and the long XMM observation than from the long XMM observation to the newest *Chandra* observation, the fractional change in the X-ray luminosity expected from a tidal disruption event is expected to be smaller in the second period of time than the first. Additionally, the source was not detected with Einstein. The upper limits from Einstein are about  $\sim 10^{40}$  ergs/sec (Harris et al. 1993) – this would also be a problem for a tidal disruption model.

It has additionally been suggested that the optical line emission from XMMU 122939.7+075333 might have been produced through the tidal detonation of a WD, rather than a tidal destruction (Irwin et al. 2010), a scenario previously modelled by Rosswog et al. (2009). Tidal detonation requires the production of enough iron that one would expect to see iron lines in the optical spectra unless the explosion products were inhomogeneous in a fine-tuned manner. Additionally, Rosswog et al (2009) suggest that the only difference between the long term X-ray variability of a detonation and a disruption event is that the total mass reservoir in a detonation event is likely to be a factor of  $\sim 3$  smaller; the problems in explaining the long-term lightcurve of the source thus remain.

The strong X-ray variability we report in this paper therefore cannot be due to the secular evolution of an accreting intermediate mass BH system which has tidally disrupted a WD. In IMBH scenarios, the accretion will be at well below the Eddington rate. As a result, strong disk winds are unlikely to develop. The short timescale variability seen on 1 January 2004 is thus difficult to explain, and it is also then difficult to explain the longer timescale variability through changes in foreground absorption.

### 3.3 Pure absorption changes

We can also consider the effects of changing only the foreground  $N_H$  without changing the intrinsic luminosity of the source. Oosterbroek et al. (1997) observed the 1989 outburst of V404 Cyg and found that its spectral variability was well fitted by including a variable  $N_H$  which ranged from  $5 \times 10^{22}$  to  $1.6 \times 10^{23} \text{ cm}^{-2}$  near the peak of the source’s outburst, when it is likely to have been in a super-Eddington state. It then seems reasonable that a change in  $N_H$  of  $\sim 10^{23} \text{ cm}^{-2}$  is possible for very bright X-ray sources. Using W3PIMMS, we compute the count rate expected for this source if it is modelled by a 0.2 keV blackbody with an intrinsic luminosity of  $4 \times 10^{39}$  ergs/sec with a foreground absorption of  $10^{23} \text{ cm}^{-2}$ , and find that the expected count rate on ACIS-S is about  $1.5 \times 10^{-5}$  counts/sec – a factor of about 10 below our detection limit. It is thus possible that the source has not varied intrinsically, and that just the foreground absorption has varied. The non-detection with Swift in March of 2010 argues (albeit only at the  $\sim 3\sigma$  level) against a change in absorption as the reason for the fading seen in the *Chandra* observations, unless that change is rather long lived. It should be noted that such a long-lived change might be expected for the case for a disk wind from a precessing disk (if e.g. the inclination angle of the disk wind changed from one

from not intercepting the line of sight to one intercepting it), and that the one Galactic X-ray binary with a strong, persistent disk wind, SS 433 (Blundell et al. 2001) is well known to have a strong precession (e.g. Margon 1984).

If the X-ray variability is due to real changes in the central engine luminosity, then the [O III] luminosity should respond to those changes on a light travel time; if it is due to changes in the absorption, the response of [O III] should be much weaker, since most of the photoionizing emission is directed along lines of sight other than the one between the source and the Earth. An approved *Chandra* + *Gemini* campaign will provide the first test of whether the X-ray source is still on, and whether the [O III] luminosity has responded to any changes in X-ray luminosity.

We note that we have done these calculations assuming that the absorbing material has the cosmic abundances of Morrison & McCammon (1983), which are embedded within W3PIMMS, rather than the nearly hydrogen-free abundances expected on the basis of the optical spectra of RZ 2109. Since the extinction in the soft X-rays is predominantly due to carbon and oxygen, it is not intrinsically problematic that there is no hydrogen present. The column densities of carbon and oxygen will be nearly the same in a hydrogen-free absorber as they would be in a solar composition absorber with the fitted  $N_H$ .

## 4 CONCLUSIONS

We have reported large amplitude X-ray variability from XMMU 122939.7+075333, the first strong candidate for being a BH X-ray binary in a globular cluster. We have shown that the combination of X-ray luminosity, X-ray variability on both short and long timescales, and optical line emission are all consistent with the idea that this system is, rather than being an X-ray binary, a hierarchical triple system with its inner binary composed of a WD and a stellar mass BH. Better sampling of the long timescale X-ray variability of the system is needed to test this idea more thoroughly. We have also shown that in the proposed scenario in which the system has an intermediate mass BH accretor has serious problems reproducing both the short and long term variability.

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<sup>2</sup> We have accessed this catalog from Vizier rather than from the original paper catalog.